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A simple model of the effect of ocean ventilation on ocean heat uptake

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Earth System Models vs. Simple Climate Models

- Comprehensive Earth System Models
  - Best available tool for understanding climte
  - But large computational burden
  - Quantifying uncertainty difficult if not impossible
- Simple Climate System Models
  - Based on essential integral balances; e.g., energy, water mass
  - Conceptual models of heat transfer in the climate system
  - Computationally cheap
  - Can be calibrated against ESMs; amenable to UQ
  - Useful in policy, integrated assessment, etc...
- Would like an SCM to reproduce a range of simulated and observed surface and subsurface warming scenarios

A Popular SCM: Energy Balance Model of Anomalies

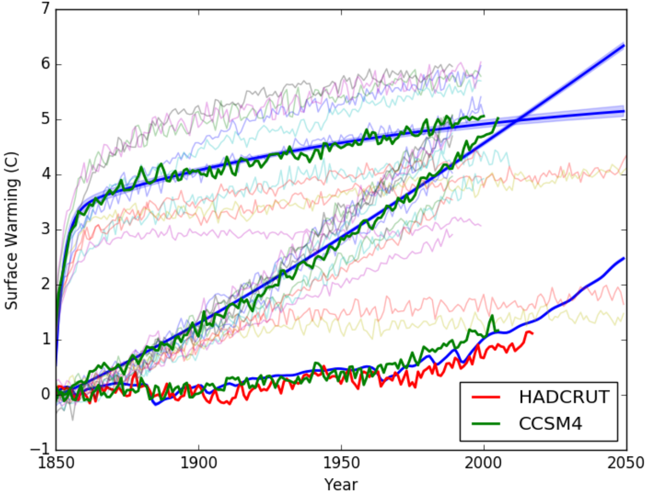
$$C_m \frac{\partial T_s}{\partial t} = F - \lambda T_s - \Delta F$$

$$\frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} = \kappa_v \frac{\partial^2 T}{\partial z^2}$$

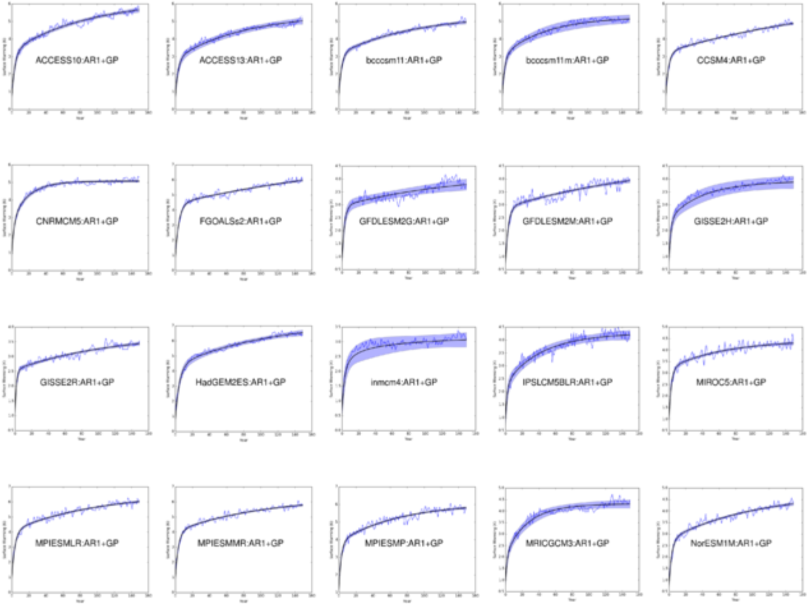
$$T(t) = T_{obs}(t) + \epsilon(t)$$

$\epsilon(t)$: Natural Variability (High Frequency + Low Frequency)

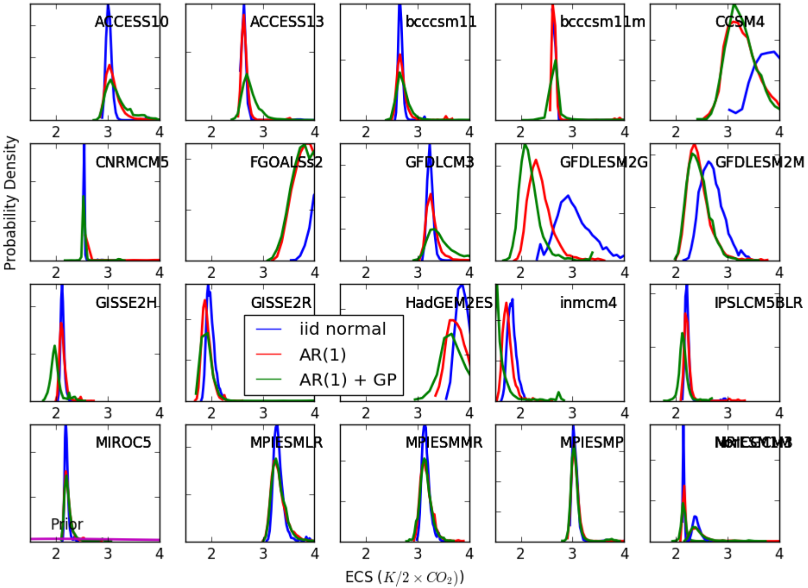
On calibrating against one ESM experiment, the SCM correctly captures that ESM's surface warming response with other forcings



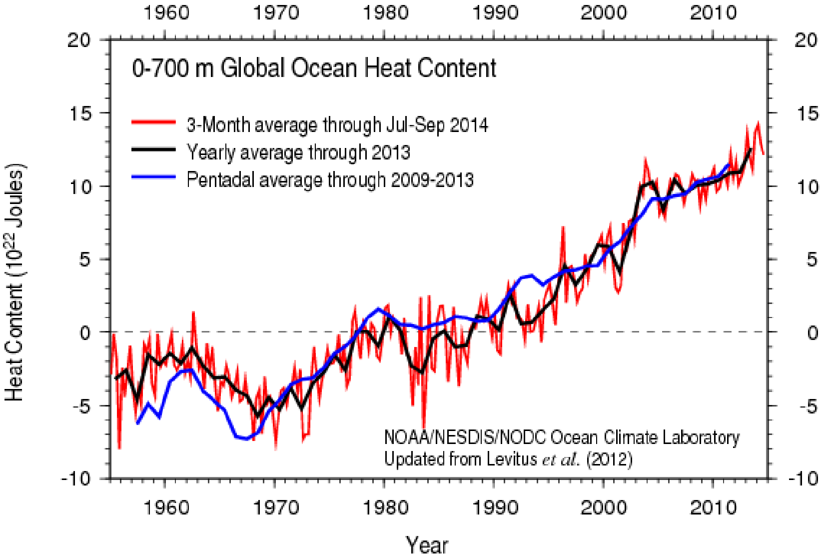
Multi-Model Analysis: Multiple ESMs, Single SCM



Posterior Distributions of ECS



However In Excess of 90% of TOA Energy Imbalance is Sequestered in the World Oceans

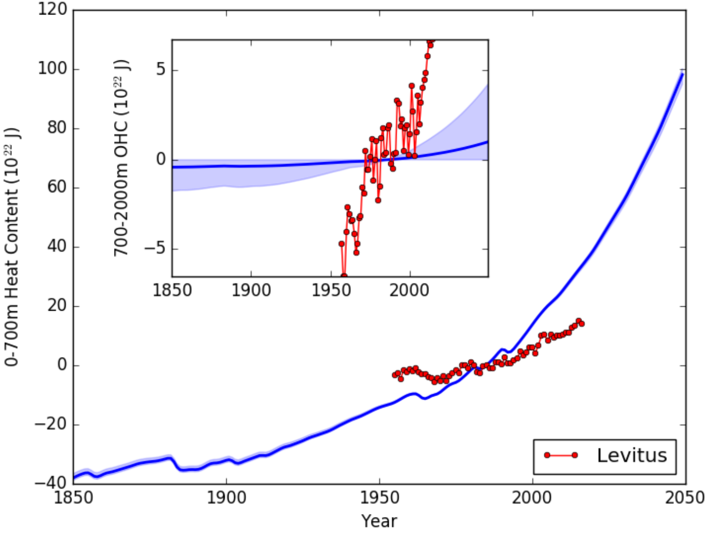


Heat Storage in the Two Layer Model

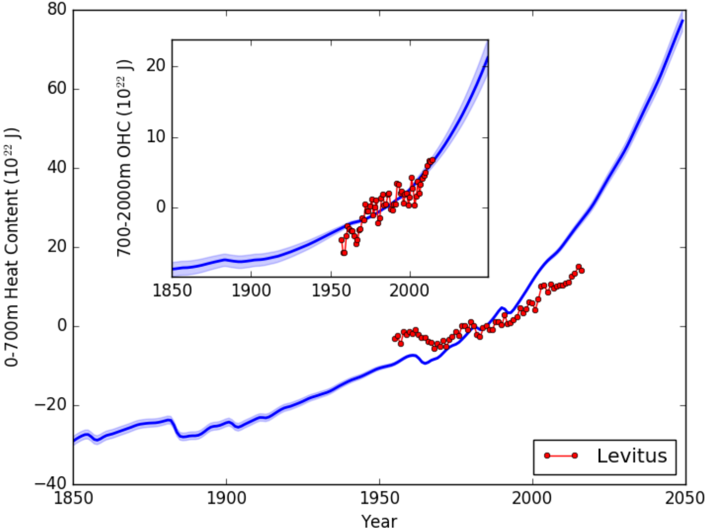
$$
\begin{aligned}
C_u \frac{dT_u}{dt} &= \mathcal{F} - \lambda T_u - \gamma\,(T_u - T_d) \\
C_d \frac{dT_d}{dt} &= \gamma\,(T_u - T_d) \\
\frac{d\mathcal{H}}{dt} &= \mathcal{F} - \lambda T_u \\
\mathcal{H} &= C_f T_f = C_u T_u + C_d T_d \\
&= \rho C_v (D_u T_u + D_d T_d) \\
&= C(D_u T_u + D_d T_d)
\end{aligned}
$$

Heat Storage in the Two Layer Model

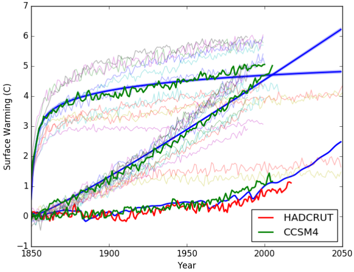
Calibrated only against surface warming

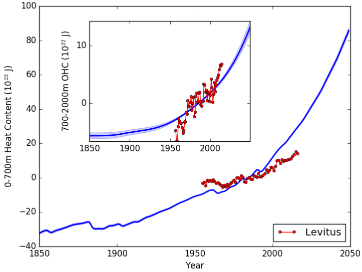


Including TOA Rad. Imbalance and Ocean Heat in Calibration Improves Repr., but Significant Errors Persist



Improved Vertical Resolution Does Not Fix Problem





Cannot simultaneously properly represent surface warming and the 0-700m and 700-2000m heat storage even with 60 layers.

A Series of Expts. Confirms That Anomaly-Diffusing Models Cannot Properly Represent Ocean Heat Uptake

Table 1 A brief overview of the experiments conducted.

Expt. #	SCM	Calibration Details			Comment
		Forcing	ESM Response	Obs. Data	
1	2L	4x	SAT		Good SAT; Poor OHC
2	2L	4x	SAT, RN		Good SAT; Poor OHC
3	2L	4x	SAT, RN		Reasonable SAT Improved OHC
		Historical		0-700m OHC 700-2000m OHC	
4	3L/4L	4x	SAT, RN		Same as in Expt. 3
		Historical		0-700m OHC 700-2000m OHC	
5	40L/60L many variants	4x	SAT, RN		Degraded 4x SAT Poor OHC
		Historical		0-700m OHC 700-2000m OHC	
6	4LE	4x	SAT, RN		Reasonable SAT Reasonable OHC
		Historical		0-700m OHC 700-2000m OHC	

A Series of Expts. Confirms That Anomaly-Diffusing Models Cannot Properly Represent Ocean Heat Uptake

Expt. #	SCM	Comment
5a	40L; MLD inferred κ_v^{TC} inferred $\kappa_v^{ML_{bot}} = \kappa_v^{TC}$	Degraded 4x SAT Poor OHC
5b	40L MLD = 70 m	Degraded 4x SAT Poor OHC
5c	40L $\kappa_v^{ML_{bot}} \neq \kappa_v^{TC}$ $\kappa_v^{ML_{bot}}, \kappa_v^{TC}$ inferred	Degraded 4x SAT Poor OHC
5d	40L $\kappa_v^{TC} = 10^{-5}$ m^2/s $\kappa_v^{ML_{bot}} \neq \kappa_v^{TC}$	Poor SAT Poor RN Poor OHC
5e	40L; w inferred $\kappa_v^{ML_{bot}} \neq \kappa_v^{TC}$ $\kappa_v^{ML_{bot}}, \kappa_v^{TC}$ inferred	Same as in Expt. 5c Degraded 4x SAT Poor OHC
5f	40L; $\kappa_v^{>650m}$ inferred $\kappa_v^{ML_{bot}} \neq \kappa_v^{TC}$ $\kappa_v^{ML_{bot}}, \kappa_v^{TC}$ inferred	Same as in Expt. 5c Degraded 4x SAT Poor OHC
5g	60L; Same as 5c	Same as in Expt. 5c
7	40L; Same as 5c Non-local interaction	Reasonable SAT Reasonable OHC

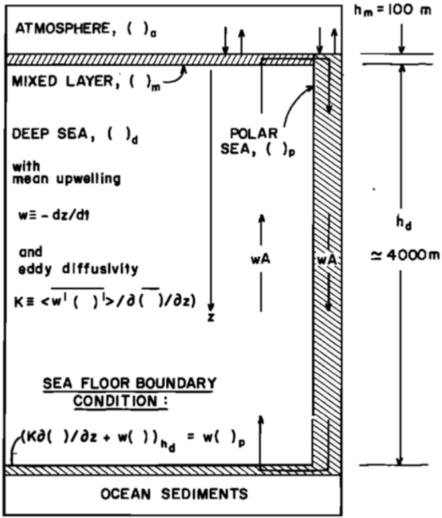
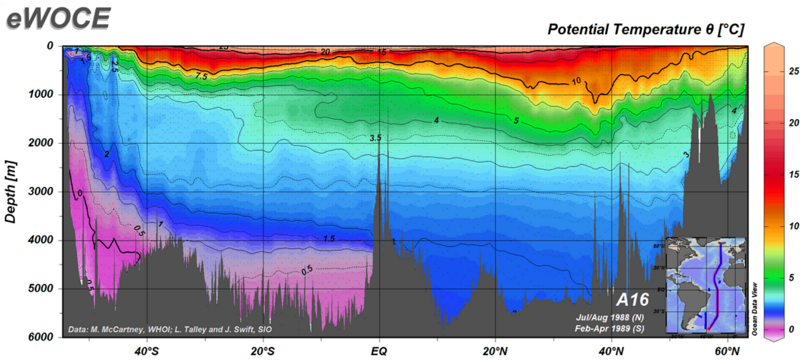


Fig. 1. Schematic diagram of one-dimensional upwelling-diffusion world ocean model showing recirculation of water upwelled over oceanic horizontal area by downwelling in the polar sea. The sea floor boundary condition equates the polar sea downwelling flux to the net (upwelling plus diffusion) upward flux into the world ocean.

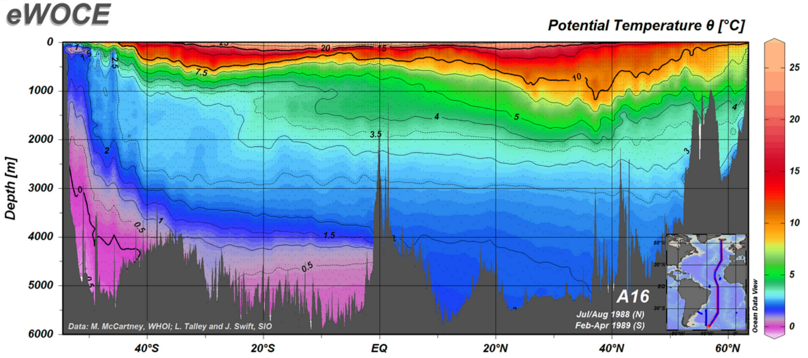
Hoffert et al., 1980

Physics of the Thermocline



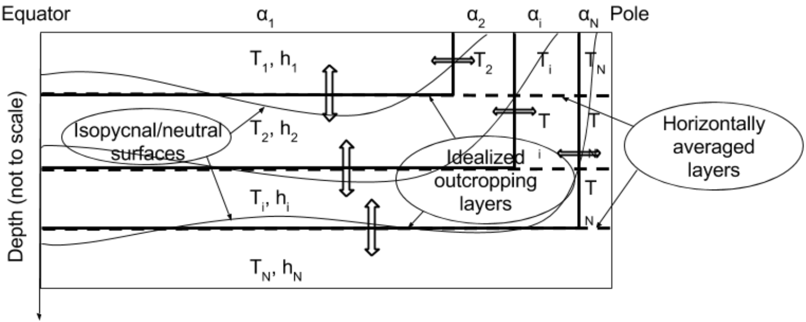
- Water mass characteristics set
  - By direct interaction with atmosphere
  - Interior transport (mixing is small)
- Determines internal structure (horizontal and vertical)
- Influences ocean response and climate variability/change

Physics of the Thermocline



- Largely Adiabatic Outside of Mixed Layer
- Sub-Tropical & Sub-Polar Mode Water Formation: Winter ML sets properties; slides down ventilated isopycnals
- Higher Latitude Deep Water Formation
- Large scale weak upwelling
- Weakly Diffusive (un-ventilated regions)

Outcropping Isopycnals and Horizontally-Averaged Layers



Thin curved lines: Outcropping isopycnal/neutral surfaces
Thick straight lines: Simplified repr. of outcroppping surfaces
Dashed straight lines: Horizontally-averaged layers

Local interactions between outcropping isopycnals leads to non-local interactions between horizontally-averaged layers

$$c\left(\alpha_i \sum_{j=1}^{i-1} h_j + h_i \sum_{j=1}^{i} \alpha_j\right) \frac{dT_i}{dt} = \alpha_i \left(\mathcal{F} - \lambda T_i\right) + \sum_{j=\max(1,i-1)}^{\min(N,i+1)} \gamma_{ij} (T_j - T_i)$$

$$\frac{d\mathbf{T}}{dt} = \mathbf{C} + \mathbf{AT}$$

$$\sum_{j=i+1}^{N} \alpha_j T_j + T_i \sum_{j=1}^{i} \alpha_j = \widetilde{T}_i$$

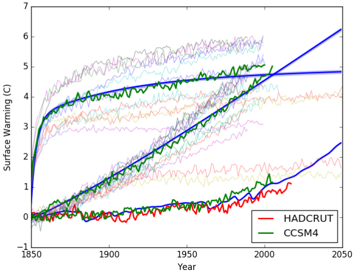
$$\mathbf{BT} = \widetilde{\mathbf{T}}$$

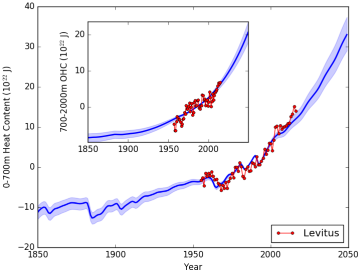
$$\mathbf{T} = \mathbf{B}^{-1}\widetilde{\mathbf{T}}$$

$$\frac{d\widetilde{\mathbf{T}}}{dt} = \widetilde{\mathbf{C}} + \widetilde{\mathbf{A}}\widetilde{\mathbf{T}}.$$

$$\widetilde{A}_{ij} = \sum_{k=1}^{n} \sum_{l=1}^{n} B_{ik} A_{kl} B^{-1}_{lj} = \sum_{k=i}^{n} \sum_{l=1}^{j} B_{ik} A_{kl} B^{-1}_{lj}$$

Both Surface Warming and Ocean Heat are Well Represented With Just 4 Layers





A Series of Expts. Confirms That When Non-Local Interactions are Allowed, the SCMs Can Represent Both Surface Warming and Ocean Heat Uptake

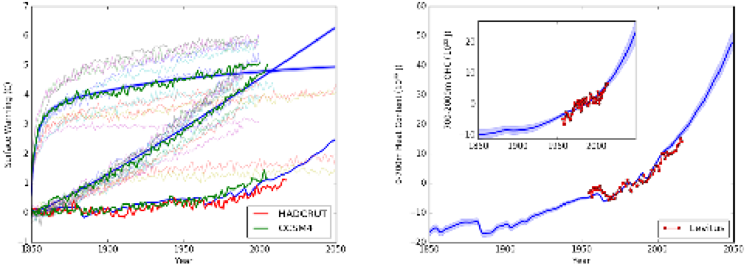


Fig. 12 In Experiment 7, a modification of the continuously-stratified model to allow for a non-local interaction—motivated by the direct sequestration of heat by deepwater formation processes—is seen to be able to simultaneously represent surface warming and the 0-700m and 700-2000m heat storage in a reasonable fashion.

Summary and Conclusions

- Comprehensive ESMs cannot be run long enough
  - to determine useful measures such as climate sensitivity or
  - perform various interesting kinds of mathematical and statistical analysis
  - EMICs or SCMs are needed to interpret ESMs
- A popular SCM is considered and is found to be unable to simultaneously represent both SAT and vertical distribution of heat uptake
- A parameterization of deepwater formation and subduction is shown to resolve this deficiency
- This parameterization is seen to improve the performance of a newly developed model of an entirely different nature.

Summary and Conclusions

- At the same level of computational cost/complexity, one can formulate better models than are currently being used to characterize ESMs and explain observations
- Including subduciton/deep-water seems necessary to explain ESM and observed ocean heat uptake
- Simple Climate Models have a use in interpreting and better understanding comprehensive Earth System Models.
- With SCMs, can quantify uncertainty and use a variety of other tools that can't be used with ESMs